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Patentanmeldung Nr. **Patent application No.** **Demande de brevet n°**

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Der Präsident des Europäischen Patentamts;
Im Auftrag

For the President of the European Patent Office

Le Président de l'Office européen des brevets
p.o.

R C van Dijk

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Bezeichnung der Erfindung/Title of the invention/Titre de l'invention:
(Falls die Bezeichnung der Erfindung nicht angegeben ist, siehe Beschreibung.
If no title is shown please refer to the description.
Si aucun titre n'est indiqué se referer à la description.)

Hologaphic data storage 3

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Holographic data storage 3

Optimized read-out in holographic data storage

Abstract

Holographic data storage (HDS) has the potential to obtain large storage densities, fast parallel access, rapid searches in large databases and data encryption. In this invention disclosure a method is proposed to gain about a factor 2 in read-out power and signal strength for a transmittive and semi-reflective (phase-conjugate) HDS system. About a factor 2 and about a factor 4 are gained in the read-out power and the signal strength during readout of a holographic data storage medium, when the invention is implemented in a full-reflective holographic system, respectively.

State of the art and problem

A 50/50 beam splitter is used in HDS systems to split the laser beam in a reference beam (or reference wave) along a first optical path and a data (or signal) beam (or signal wave) along a second optical path.

In some systems the reference beam used during recording is used as read-out beam during readout (see Figure 1), while in other systems for example a phase conjugated reference beam (wave) is used as readout beam (see Figure 2). Other examples are presented in the descriptions of the figures.

Sometimes the first optical path for the reference beam is referred to as reference branch.

During readout the 50/50 beamsplitter is also used for creating the readout beam out of the laser beam. As a consequence half of the laser light is not used during read-out of the medium (Figure 1-Figure 3).

Solution

A polarizing beam splitter (PBS) is used instead of the 50/50 beam splitter (for examples see Figure 4 to Figure 9) to split the laser beam in a reference beam and a data (or signal) beam. The polarization of linear polarized light from the laser, e.g. p-polarized light, is rotated 45° by rotating the half-wave plate (½λ-plate) under an angle of 22.5° relative to the optical axis of the crystal. The PBS splits the 45° rotated linear polarized beam into a p-polarized data (or signal) beam and an s-polarized reference beam. In the reference beam a second ½λ-plate is positioned in an orientation. With a predetermined orientation of this second ½λ-plate the s-polarized reference beam can be transform during the recording phase into a p-polarized beam. The data beam is encoded with a data encoder (for instance a two dimensional spatial light modulator) into an encoded data beam. As both encoded data beam and reference beam have the same polarization they can create an interference pattern in an overlapping area at the medium.

During read-out the ½λ-plate is rotated back to its optimal position (45° relative to the optical axis of the crystal) and converts the p-polarized laser light into s-polarized light. All the s-polarized light passes through the PBS increasing the power of the readout beam during read-out with a factor 2 and the signal strength with a factor 2 or 4.

CLAIM:

A holographic data storage device for recording in and/or reading out data from a holographic data storage medium, said device comprising a light-source, a polarizing beamsplitter splitting a laserbeam into a reference beam along a first optical path and a data beam along a second optical path, a rotatable first half-wave plate between said light source and said polarizing beamsplitter and a second half-wave plate in an orientation in said first optical path of the reference beam between said polarizing beamsplitter and said medium.

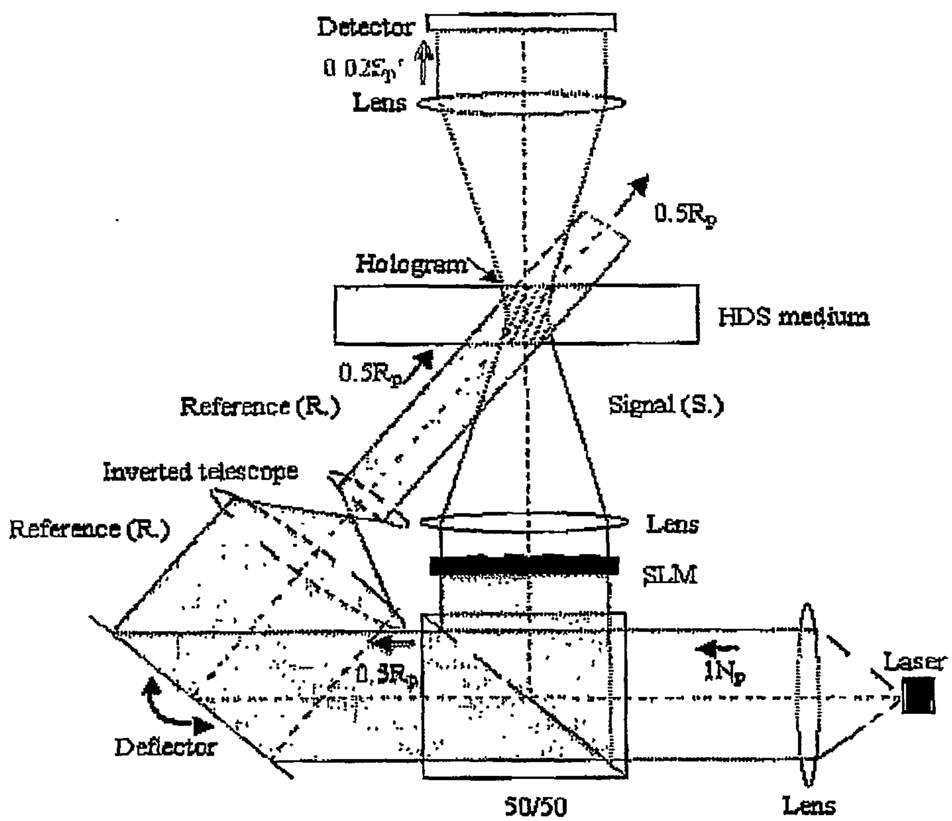


Figure 1. Example of a prior art transmissive holographic read-out system based on angular multiplexing.

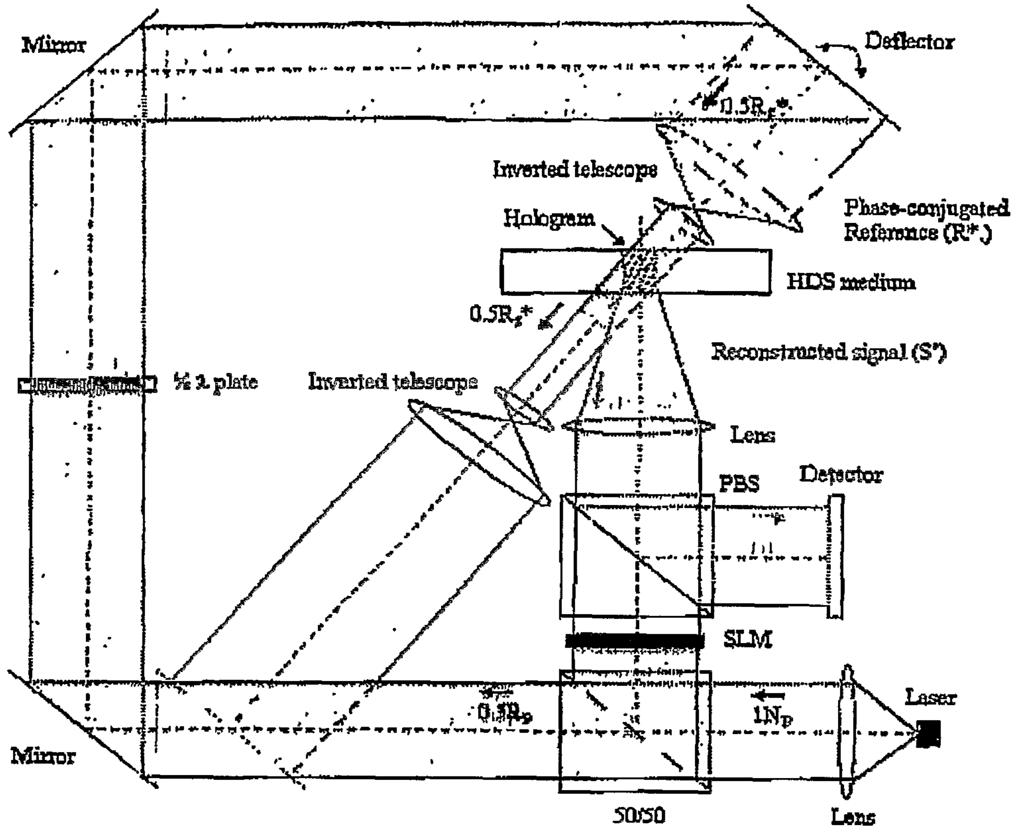


Figure 2. Example of a prior art phase-conjugate holographic read-out system based on angular multiplexing.

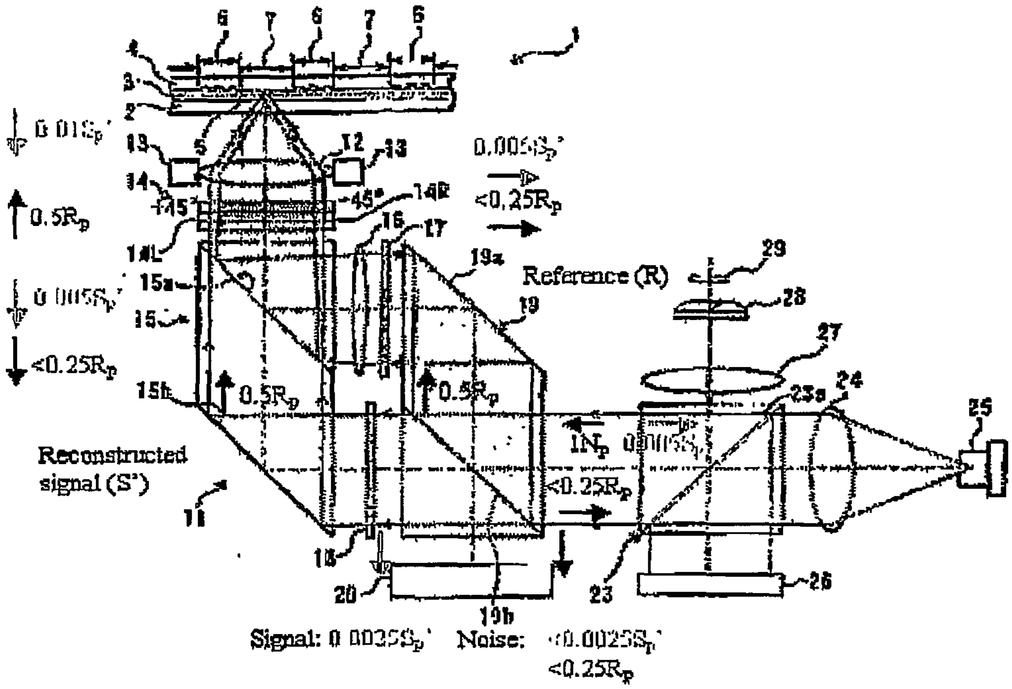


Figure 3. A full reflective holographic read-out system based on phase-coded multiplexing.

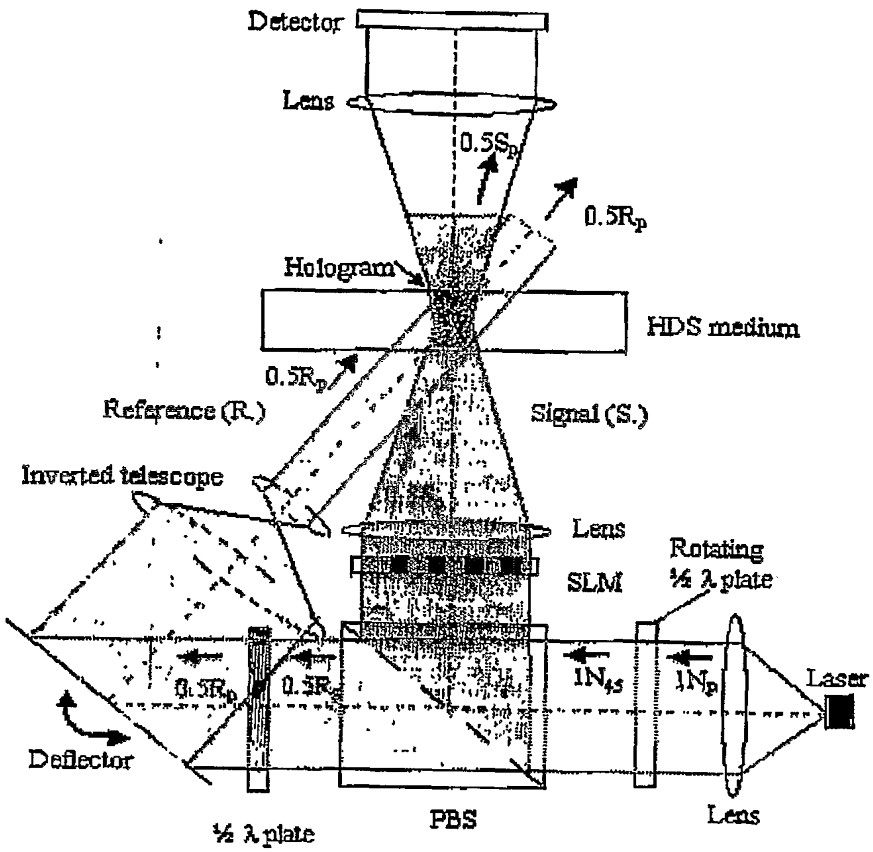


Figure 4. Proposed embodiment implemented in a prior art transmissive holographic recording system based on angular multiplexing. P-polarized laser light is converted into circular polarized light using a rotating ½λ-plate and split with a PBS in a s-polarized reference wave and a p-polarized signal wave. The s-polarized reference wave is converted into a p-polarized wave with a ½λ-plate in a predetermined orientation in the reference branch.

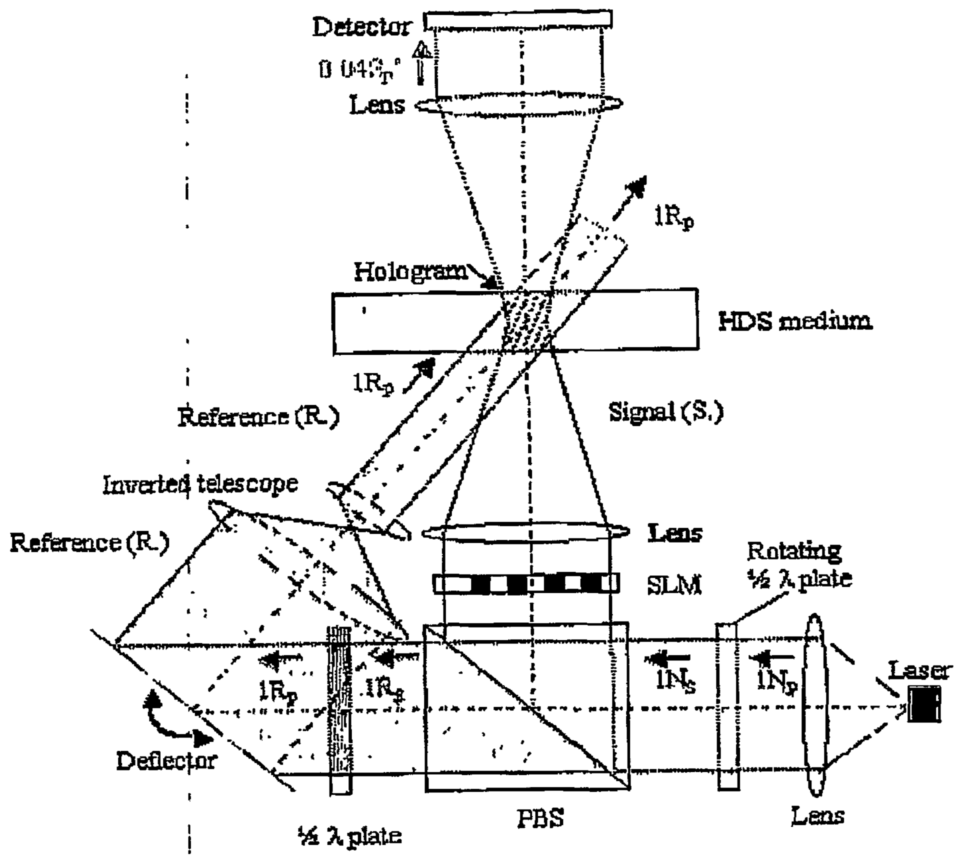


Figure 5. Proposed embodiment implemented in a prior art transmissive holographic read-out system based on angular multiplexing. P-polarized laser light is converted into s-polarized light using a rotating ½λ-plate. All the s-polarized light is transmitted through the PBS into the reference branch and converted to a p-polarized wave with a ½λ-plate in a predetermined orientation in the reference branch. The power in the reference branch and the signal strength is increased with a factor 2.

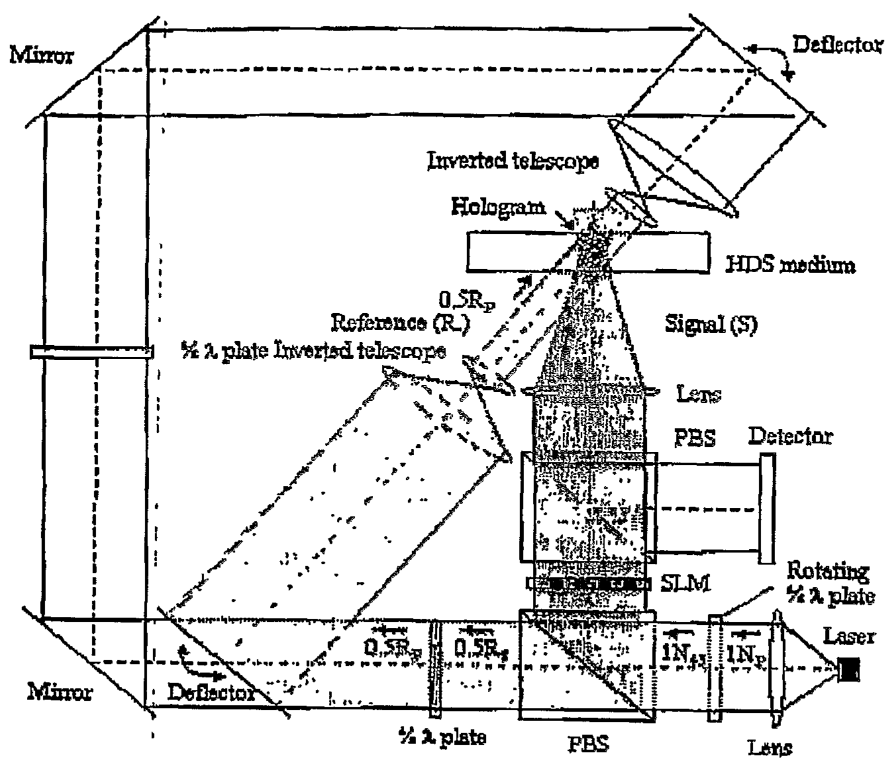


Figure 6. Proposed embodiment implemented in a prior art phase-conjugate (semi-reflective) holographic recording system based on angular multiplexing. P-polarized laser light is converted to circular polarized light using a rotating ½λ-plate and split with a PBS in a s-polarized reference wave and a p-polarized signal wave. The s-polarized reference wave is converted to a p-polarized wave with a ½λ-plate in a predetermined orientation in the reference branch.

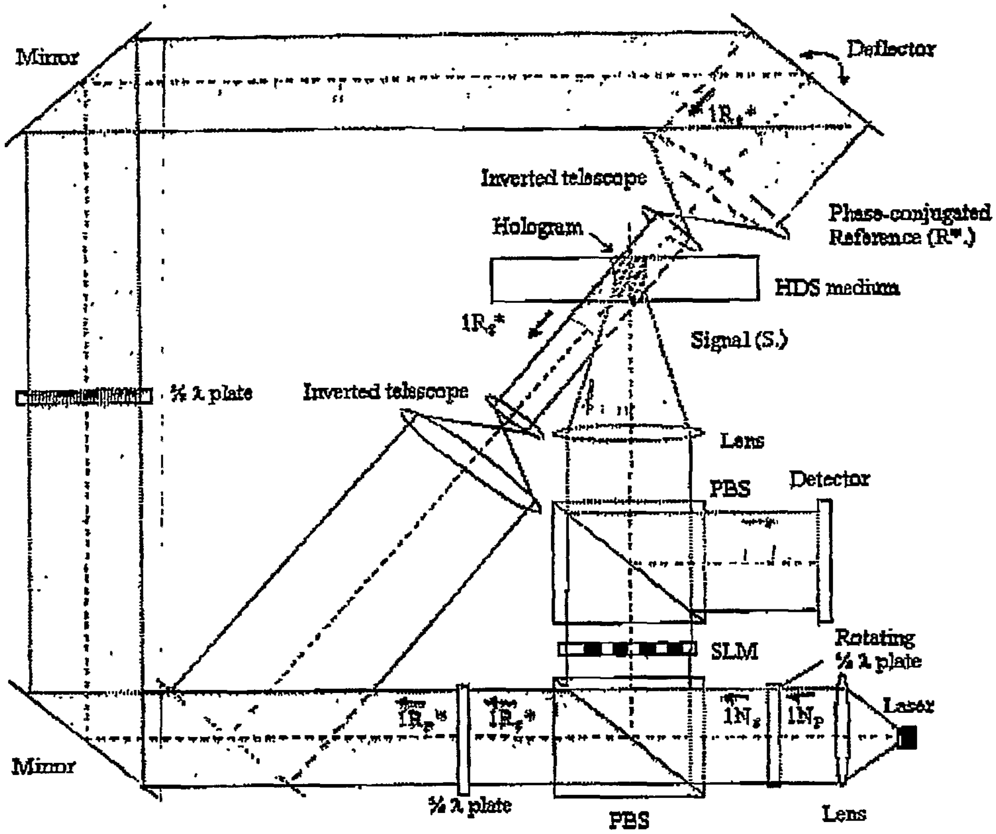


Figure 7. Proposed embodiment implemented in a prior art phase-conjugate (semi-reflective) holographic read-out system based on angular multiplexing. P-polarized laser light is converted into s-polarized light using a rotating ½λ-plate. All the s-polarized light is transmitted through the PBS into the reference branch and converted back into s-polarized light with two ½λ-plates (each of the ½λ-plates in a predetermined orientation) in the phase-conjugate reference branch. The power in the phase-conjugate reference branch and the signal strength is increased with a factor 2.

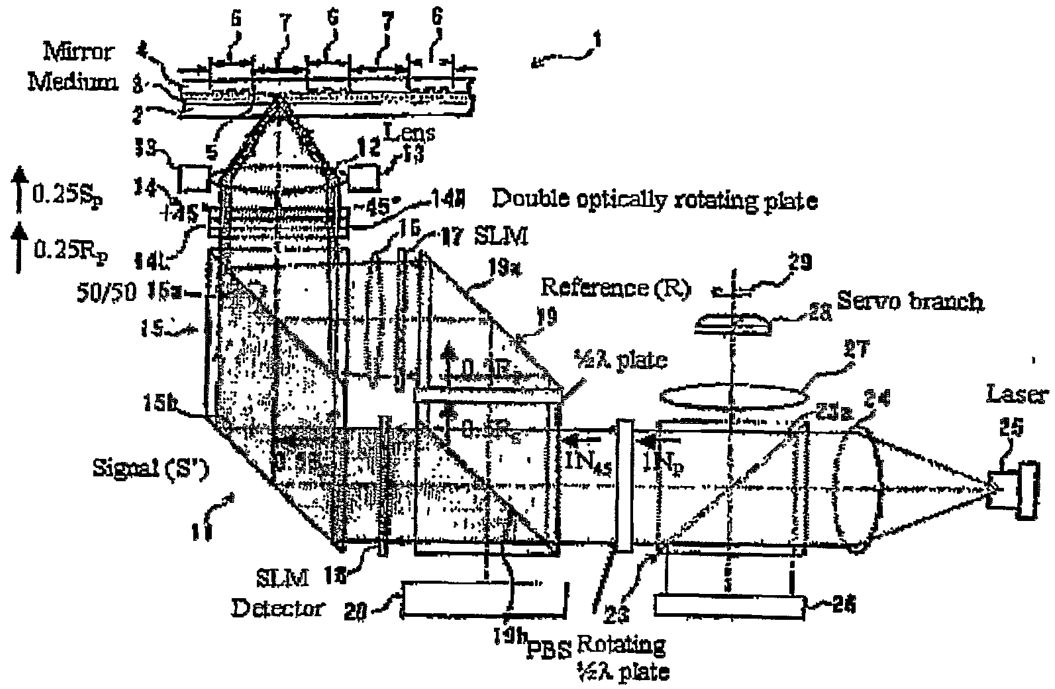


Figure 8. Proposed embodiment implemented in a prior art full reflective holographic recording system based on phase-coded multiplexing. P-polarized laser light is converted into circular polarized light using a rotating ½λ-plate and split with a PBS in a s-polarized reference wave and a p-polarized signal wave. The s-polarized reference wave is converted to a p-polarized wave with a ½λ-plate (in a predetermined orientation) in the reference branch.

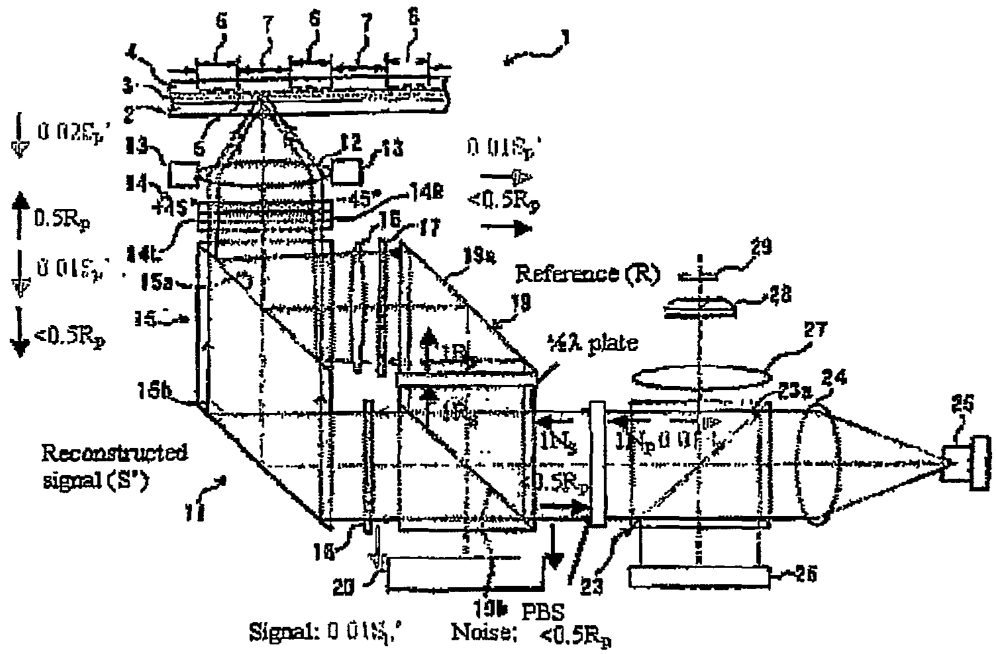
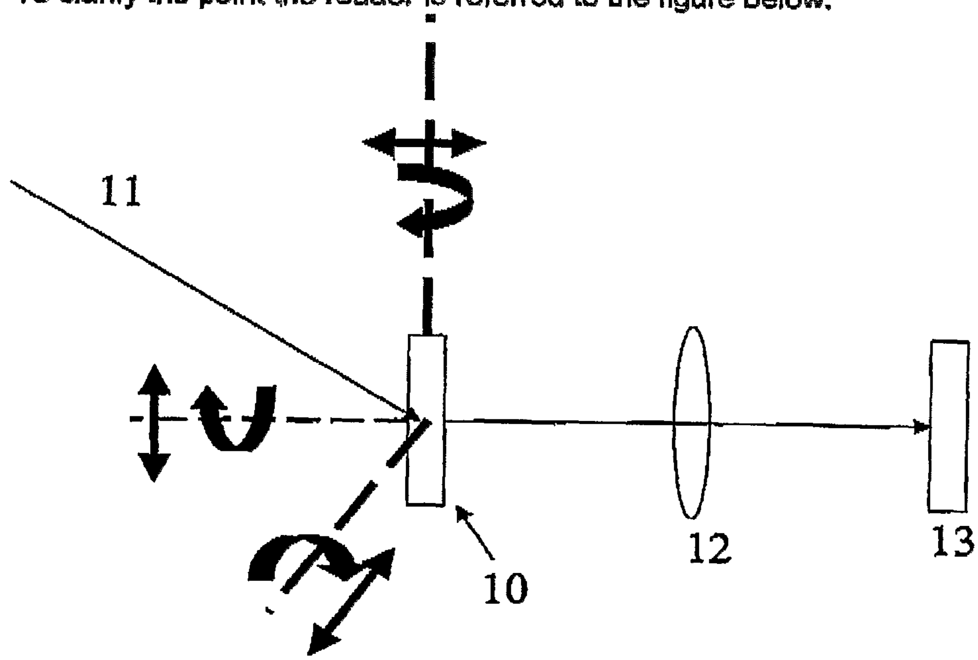


Figure 9. Proposed embodiment implemented in a prior art full reflective holographic read-out system based on phase-coded multiplexing. P-polarized laser light is converted into s-polarized light using a rotating ½λ-plate. All the s-polarized light is reflected by the PBS into the reference branch and converted into p-polarized light with a ½λ-plate (in a predetermined orientation) in the reference branch. The power in the phase-conjugate reference branch is increased with a factor 2 and the signal strength increases with a factor 4 due to the reflection of 100% of the backwards-reconstructed signal wave by the PBS.

Alignment method for a holographic storage system

Introduction

One of the major issues in holographic data storage systems is the alignment sensitivity of the holographic storage medium with respect to the pixelated detector (e.g. a two-dimensional detector array)
To clarify the point the reader is referred to the figure below.



We have a holographic storage medium 10 were the recorded data is organized in pages, which is being read out by impinging a readout laser beam 11 on it at a particular angle. As a result of diffraction upon a grating inscribed/recorded in the medium (recorded datapages), some of the intensity of the readout laserbeam 11 is diffracted (and alternatively guided by means of a lenssystem 12) towards a pixelated detector 13 (the recorded data page is imaged as imaged data page on the pixelated detector). There are many degrees of freedom in the system (at least 6 for the medium alone), and some of them are indicated in the figure. The key issue in retrieving reliable data with such a system is also determined by mutual alignment errors between an imaged data page and a pixelated detector as represented by the following parameters:

1) **Magnification**: the magnification of the lenssystem should be such that every resulting bit in the imaged hologram should impinge on one pixel of the

pixelated detector. Methods have been proposed by others to "oversample", i.e. using for instance 4 detector-pixels per bit stored in the medium, but this leads to an over-dimensioned detector array, and hence higher cost, and size.

2) **Focus**: The imaged bits should be focussed upon the pixelated detector, in order to obtain the highest correlation between bits and readout of the detector pixels.
3) **Rotation**: Rotational degrees of freedom are to be avoided since this would lead to an angular misalignment between the pixalated detector and the imaged bits.
4) **Translation**: Translation errors are also to be avoided, since if the imaged bits falls in between the spacing of the pixalated detector, the readout signals are degraded and ambiguity arises to which pixel a certain bit belongs and hence data readout errors occur.

Problem

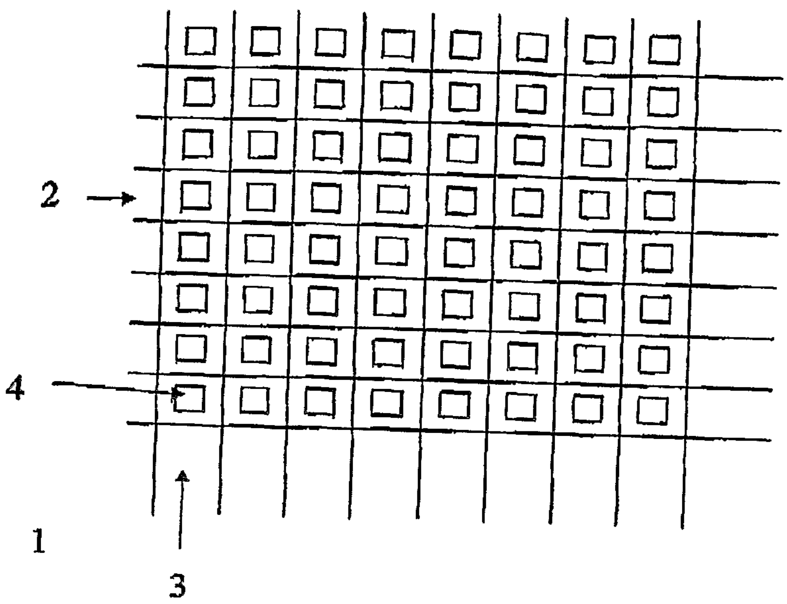
Methods to find a solution to these issues are being sought into tight mechanical tolerances, the oversampling mentioned above, and in the use of alignment marks.

The latter solution is comparable to methods used in alignment for wafersteppers. At strategic positions on the medium one places alignment marks in the form of for instance crosses, or series of bars, and in the aligning procedure one translates and rotates in every degree of freedom to find the alignment mark and hence derives the correct settings.

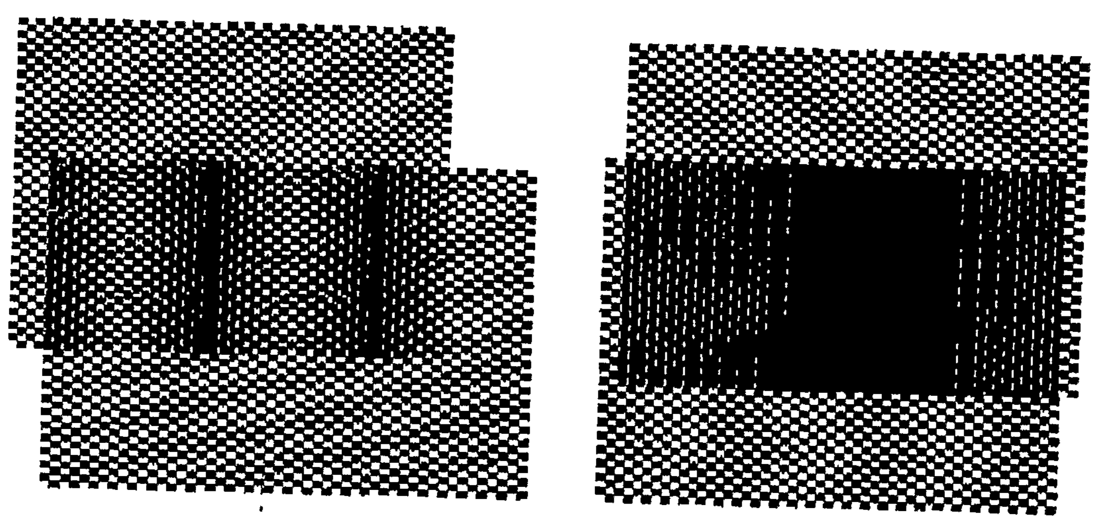
The major disadvantage of using this procedure is that it takes up space in the medium and hence lowers the attainable capacity. Furthermore, it is a time consuming activity, which in worst case has to be performed for every recorded datapage in the book in the medium. Also, in case of coarse misalignment, it will be difficult to find the correct settings, within a reasonable time.

Solution and some embodiments

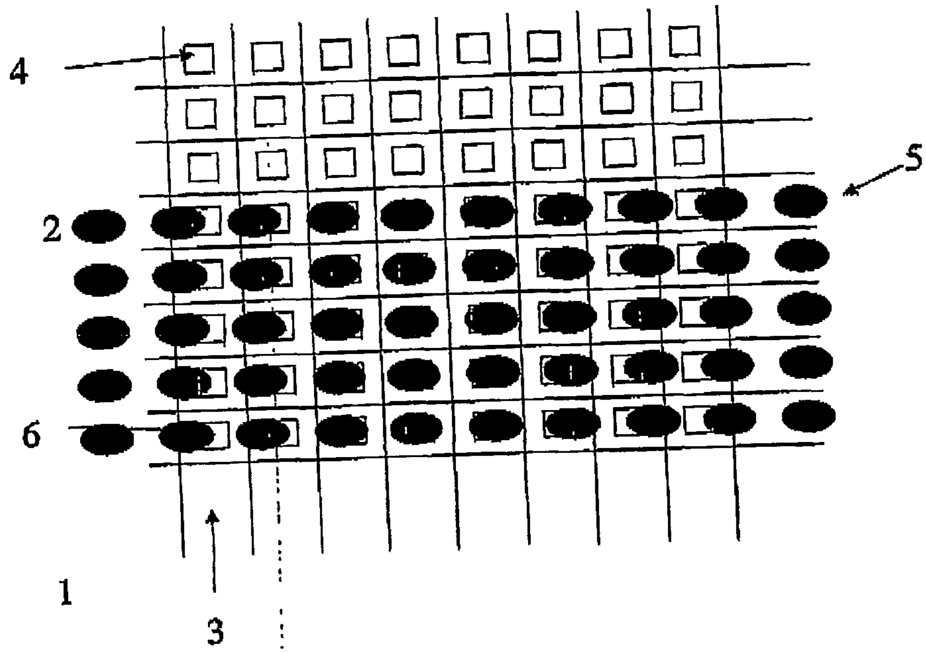
We propose to use the Moiré effect for alignment of for example the medium in the system with respect to its pixelated detector array, by using the beating between the imaged data page period and orientation on the one hand and the pixelated detector array on the other.
The generated alignment error signals, due to mutual alignment errors of the imaged data page and the pixilated detector array, can be used for alignment purposes in the device (this can also include the medium).
Consider the figure below in which we describe the layout of a typical pixelated detector array 1, containing detector-elements having an area A arranged in rows 2 and columns 3. At the intersection, the optical sensitive detector sub-area As 4 is depicted, which usually is less than the area of the detector-element. The ratio of the sub-area As over the area A called the fill-factor, which for state-of the art systems can be even below 50%.



Furthermore, consider an imaged data pattern array that should be aligned with respect to this detector array.
In case of a magnification error the resulting Moiré-pattern will resemble the situation in the figure below: on the left the matching between the two array patterns is incomplete due to a difference in size (magnification) and hence an intensity modulation (Moiré-pattern) is clearly visible. In the situation on the right hand side, the array periods are matched, and effectively the period of the occurrence of the bars in the Moiré pattern is infinite. For clarity the both arrays have also been mutually translated.

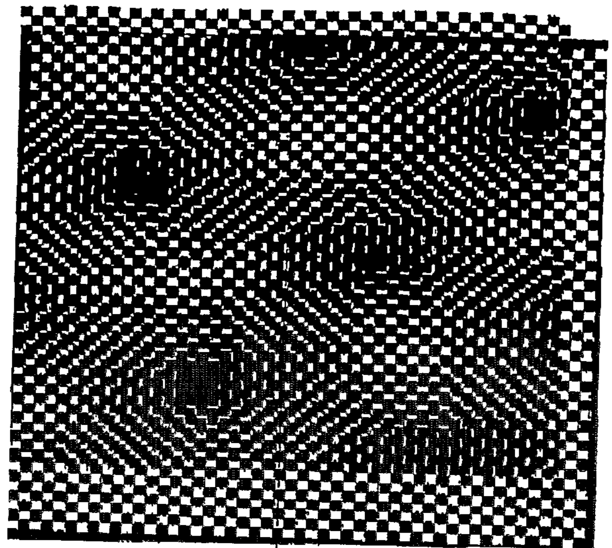


In a more detailed view the figure below shows a similar effect

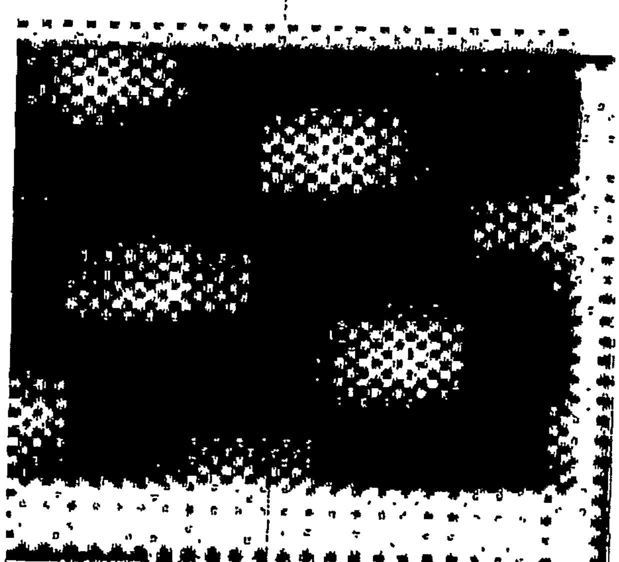


We have now positioned the image of the data array 5, on the detector array 1. The horizontal sizes are in this case different. The overlap area 6 between an imaged databit and detector pixel, the grey shaded, area is an indication of the output of an individual detector element. In the case sketched above, a horizontal modulation (vertical Moiré fringes) is observed (in the output of the detector elements), whereby the period is an indication of the magnification-error. Likewise a similar situation in vertical direction results in a modulation in the vertical direction (horizontal Moiré fringes).

Rotation can be detected and compensated by analyzing the directions of the Moiré pattern using image processing. In the figure below an example of two checkerboard masks (simulating a datapage image and a detector array) at a relative angle of 1 degree including magnification mismatch is shown.



The usual randomness of the data in the imaged data page can be filtered out by analyzing the output of the detector array in the low-frequency domain and filtering out the high frequency components of the individual sequences of databits. See figure below, which shows the image after blurring.



Perfect magnification correction is obtained whenever the periods in horizontal and vertical direction are infinite. Vertical and horizontal directions are optimized by subsequently tuning for highest output over the complete area of the detector array. Tuning for only vertical and horizontal periodic Moiré-patterns compensates rotation. Focus can for example also be found using by adjusting for optimum contrast (or high frequency components) in the detector output.

The proposed method can be used for alignment of the medium in the system, but it is also possible to use it for example for the alignment of the imaged data page or the pixilated detector array.

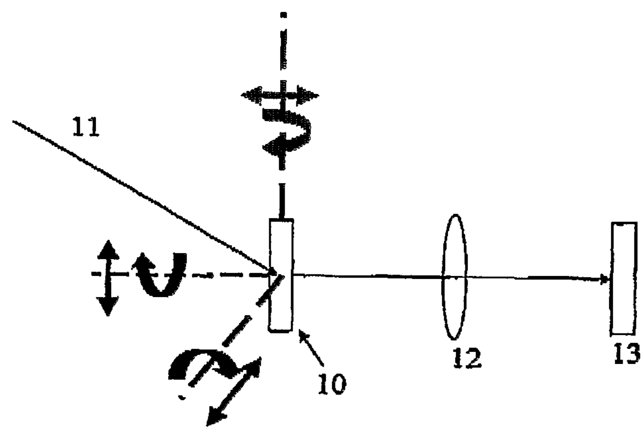
CLAIM:

A holographic data storage device for reading from and/or recording data pages in a holographic data storage medium, said device comprising a pixilated detector array for reading out an image of a data page, said device using a Moiré pattern between the image of a data page and the pixelated detector array to generate an alignment error signal representing an alignment error between said image of a data page and said pixilated detector array, said alignment error signal being used for alignment purposes in said device.

Method to compensate the misalignment in holographic systems

Problem description

One of the major issues in holographic data storage systems is the alignment sensitivity of the holographic storage medium with respect to the pixelated detector array (e.g. a two-dimensional detector array).
To clarify the point the reader is referred to the figure below.



We have a holographic storage medium 10 were the recorded data is organized in pages, which is being read out by impinging a readout laser beam 11 on it at a particular angle. As a result of diffraction upon a grating inscribed/recorded in the medium (recorded datapages), some of the intensity of the readout laserbeam 11 is diffracted (and alternatively guided by means of a lenssystem 12) towards a pixelated detector 13 (the recorded data page is imaged as imaged data page on the pixelated detector). There are many degrees of freedom in the system (at least 6 for the medium alone), and some of them are indicated in the figure. The key issue in retrieving reliable data with such a system is also determined by mutual alignment errors between an imaged data page and a pixelated detector as represented by the following parameters:

5) **Magnification**: the magnification of the lenssystem should be such that every resulting bit in the imaged hologram should impinge on one pixel of the pixelated detector. Methods have been proposed by others to "oversample", i.e. using for instance 4 detector-pixels per bit stored in the medium, but this leads to an over-dimensioned detector array, and hence higher cost, and size.
6) **Focus**: The imaged bits should be focussed upon the pixelated detector, in order to obtain the highest correlation between bits and readout of the detector pixels.
7) **Rotation**: Rotational degrees of freedom are to be avoided since this would lead to an angular misalignment between the pixalated detector and the imaged bits.
8) **Translation**: Translation errors are also to be avoided, since if the imaged bits falls in between the spacing of the pixalated detector, the readout signals are degraded and ambiguity arises to which pixel a certain bit belongs and hence data readout errors occur.

One obvious solution is to introduce mechanical displacement devices like voice-coil actuators, piezo-actuator to compensate for (as example) translational and rotational mismatch. Such systems have the drawback that they are non-robust and usually take up a lot of space; furthermore the costs are significant.

Proposed solution
We propose to introduce an optical lens-system capable of compensating for translational and magnification mismatch, for instance based on the electro-wetting principle. However, this could also be a conventional lens system or an LC-based device.
Building upon previous disclosures on the application of electro-wetting devices (like WO 031069380 A1 for focusing lens and European Patent Application 02079473.1 for the zoom function), it can be shown that these lens-systems can be constructed resulting in a very compact, low-cost system, ideally suitable for small holographic drives.

Magnification errors
It has been shown in the work on fluid-focus imagesensors that a compact zoomlens system can be constructed suitable for imaging an object onto a CCD or CMOS sensor. The current maximum zoomfactor that can be achieved lies in the range of 2-3, values we will usually not need in adjusting the mismatch we have discussed above. Typical magnification mismatch can arise due to for example changes in temperature (which can change for example the size of the medium), or due to tolerances occurring the manufacturing of the media. Preferably a 1 to 1 pixel data-bit match has to be reached in order to have a successful low-error rate data read-out.

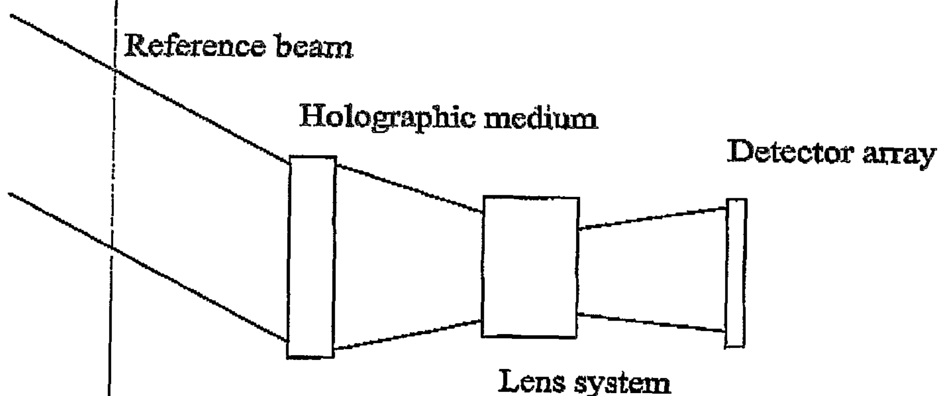
As a second advantage of using a zoomlens capable of obtaining a factor up to 2 or 3 is that a drive using a zoomlens of this type could be made backwards compatible from the start if one defines the next generations of datapages in the media having the same aspect ratio. For instance suppose a first generation of the holographic data storage systems is launched as a 1000X1000 bits square per data-page and a next generation system is defined as being a 1500x1500 system, because the detector technology has progressed to such an extend that it is economically feasible to introduce such detectors in the new system. Data-pages recorded on a medium in a first generation system can now be imaged onto the new detector in that next generation drive by adjusting the zoom-factor in such a way that again a one to one bit-pixel match is achieved; one is now able to read-out data-pages recorded using this first generation system as well as those from that next generation, be it that one uses only part of the detector array while reading out data-pages recorded in a medium of the first generation.

Apart from compatibility, even within a generation the use of a zoom-function is essential.
Detector technology progresses quite quickly, and what is now considered state of the art in pixel-pitch for instance 10 micrometer, may quickly evolve into a pitch of for instance 5-6 micrometer. When one still wants to read out the datapages with drives using either one of these detectors, it is required that a zoom-function is present.

Translation errors

Introducing, for example, wedge-shaped electrowettings device as described in European Patent Application 02080060.3 can readily compensate translational errors.

For reference we have sketched below an example of a diagram of the system described above, with a readout beam (here labeled as reference beam) impinging on the storage-medium, resulting in an image being formed and transformed through such a described lenssystem on a detector-array.



CLAIMS:

1. A holographic data storage device for reading from and/or recording data in a holographic data storage medium, the device comprising a pixelated detector array for reading out imaged data and an optical system that is adjustable for compensating alignment errors between said pixelated detector array and said imaged data.

2. A holographic data storage device according to claim 1 were the optical system comprises an electro-wetting based device.

3. A holographic data storage device according to claim 1 were the optical system comprises a liquid-crystal based device.

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